Title:

IS MAXIMUM STIMULATION INTENSITY REQUIRED IN THE ASSESSMENT OF MUSCLE ACTIVATION CAPACITY?

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Abstract

Voluntary activation assessment using the interpolation twitch technique (ITT) has almost invariably been applied using maximal stimulation intensity, i.e., an intensity beyond which no additional joint moment or external force is produced by increasing further the intensity of stimulation. The aim of the study was to identify the minimum stimulation intensity at which percutaneous ITT yields valid results. Maximal stimulation intensity and the force produced at that intensity were identified for the quadriceps muscle using percutaneous electrodes in eight active men. The stimulation intensities producing 10 to 90% (in 10% increments) of that force were determined and subsequently applied during isometric contractions at 90% of maximum voluntary contraction (MVC) via twitch doublets. Muscle activation was calculated with the ITT and pain scores were obtained for each stimulation intensity and compared to the respective values at maximum stimulation intensity. Muscle activation at maximal stimulation intensity was 91.6 (2.5)%. The lowest stimulation intensity yielding comparable muscle activation results to maximal stimulation was 50% (88.8 (3.9)%, $p < 0.05$). Pain score at maximal stimulation intensity was 6.6 (1.5) cm and it was significantly reduced at 60% stimulation intensity (3.7 (1.5) cm, $p < 0.05$) compared to maximal stimulation intensity. Submaximal stimulation can produce valid ITT results while reducing the discomfort obtained by the subjects, widening the assessment of ITT to situations where discomfort may otherwise impede maximal electrostimulation.

Introduction

Muscle strength, measured as joint moment or force applied externally during a maximum voluntary contraction (MVC), is determined by a number of biological factors, including the size of the agonist muscles and their moment arms, the joint angle tested which affects muscle length, the specific tension of the muscle, antagonist muscle co-contraction, and the level of voluntary agonist muscle activation during the test. The assessment of this last factor, voluntary activation, requires the application of artificial stimulation and this has been routinely applied in several populations, including children [O’Brien et al, 2010; O’Brien et al, 2008], older individuals [Morse et a,. 2008; Reeves et al, 2003], patients with musculoskeletal disorders [Rutherford et al, 1986; Suter et al, 1998] and in intervention studies involving various types of exercise training [e.g., Knight and Kamen, 2001; Maffiuletti et al, 2000; Selkowitz, 1985] and disuse [e.g., de Boer et al, 2007; Lewek et al, 2001; Sisk et al, 1987].

Voluntary activation is typically assessed by some variant of the interpolated twitch technique (ITT [Merton, 1954]), according to the equation:

$$\text{Activation level (\%)} = (1 - \text{SI} / \text{R}) \times 100 \qquad \text{(eq. 1)}$$

where, SI is the additional joint moment (or external force) produced by superimposing the electrical stimulus on the MVC and R is the joint moment (or external force) produced by the same stimulus applied at rest. Investigators generally strive to use maximal stimulation for the ITT [Babault et al, 2003; Bampouras et al, 2006; Behm et al, 2001; De Serres and Enoka, 1998; Kent-Braun and Le-Blanc, 1996; Morse et al, 2008; O’Brien et al, 2008], but there is often some confusion as to what maximality means and whether it is essential for the reliable estimation of voluntary activation. To obtain the maximum force from a muscle it is necessary that all motor units are activated and that they are stimulated at frequencies, generally in the order of 30-100 Hz [Gerritts et al, 1999], that generate maximum force. Percutaneous stimulation of a large muscle such as the quadriceps is unlikely ever to activate all motor units. Activation of all motor units can be achieved with direct stimulation of the femoral nerve. Possibly the only time that true maximality of stimulation was achieved during a voluntary contraction was with tetanic stimulation of the femoral nerve with increasing stimulus intensity [Bigland-Ritchie et al, 1978], but this is not a procedure that is well tolerated by most subjects. Irrespective of whether all motor units are activated, it is very unlikely that they will be producing their maximum force since most ITT tests involve using twitches or doublets rather than tetanic trains.

One issue associated with using twitches or doublets to stimulate the resting muscle is that the relatively small and transitory forces will be recorded as smaller tension transients due to stretching of the series elastic components of the apparatus and in the muscle-tendon unit. When superimposed on a voluntary contraction where the series elements are already stretched the tension transient will more faithfully reflect the force produced by the muscle. This will tend to increase the SI/R ratio and thus give a false low value for voluntary activation. One way of reducing the series compliance of the quadriceps is to flex the knee and it has been shown that the ITT value for the quadriceps muscle was higher by 9-18% (depending on the stimuli number) at more flexed (more stretched muscle-tendon unit) than extended (slacker muscle-tendon unit) knee positions [Bampouras et al, 2006].

Another possible way of avoiding the problems associated with comparing twitches of resting with active muscle is by using the Central Activation Ratio (CAR) which only depends on the superimposed force or joint moment during MVC and not the stimulation at rest (CAR = MVC/(MVC+SI)) [Bampouras et al, 2006]. However, it is very unlikely that the superimposed stimulation will maximally activate all the muscle.

The question is therefore how much of the muscle needs to be activated to achieve a reliable answer using the ITT. Behm et al [1996] and de Ruiter et al [2004] suggest that it is necessary to stimulate nearly all the muscle. However, Rutherford et al [1986] compared femoral nerve stimulation, which was assumed to activate all motor units, and percutaneous quadriceps muscle stimulation that activated only a portion of the muscle, and found no differences in the SI/R ratio between the two stimulation modes. When using percutaneous stimulation, Rutherford et al [1986] state that they adjusted the stimulus intensity used for the superimposed twitches in relation to the proportion of the MVC force generated when stimulating at 30 Hz. However, they did not specify what that force was nor present any evidence as to what the minimum required force might be. Consequently, the aim of the present study was to identify the minimum stimulation intensity at which muscle activation could be validly assessed, reducing the discomfort associated with high intensity stimulation and thus widening the applicability of ITT assessment to a greater range of subjects and patients.

Methods

Subjects

Eight healthy, physically active men (mean (SD): age 28.9 (5.0) years, height 1.80 (0.09) m, body mass 83.9 (15.3) kg) volunteered to participate in the study. To ensure consistency in performance, all subjects were familiar with the experimental procedures involved [Button and Behm, 2008] and were tested in the laboratory on a single occasion.

Ethical approval for the study was granted by the Ethics Committee of the Institute for Biomedical Research into Human Movement and Health of Manchester Metropolitan University, UK. All subjects provided written informed consent prior to any testing. The study complied with the Declaration of Helsinki.

Isometric knee extension test

The mechanical output of isometric knee extension was measured as force applied externally in the sagittal plane at the level of the ankle, at right angles to the longitudinal axis of the lower leg. The subjects sat in the chair of a custom-made dynamometer [de Ruiter et al, 2004; Kooistra et al, 2007], with the hip joint angle at 85^o (supine position = 0^o) and the right leg at a knee joint angle of 90^o (full knee extension = 0^o). Straps were positioned over the hips and tested thigh to prevent extraneous movement and the lower leg was securely strapped to a force-transducer (KAP, E/200 Hz, Bienfait B.V. Haarlem, The Netherlands) at the ankle. Force signals were corrected for passive tension of the knee extensors and real-time force readings were displayed online and recorded for further analysis (Matlab, The Mathworks, Natick, MA).

Electrical stimulation

Two 7 x 12.5-cm self-adhesive carbon rubber electrodes (Versa-Stim, ConMed, New York, USA) were placed on the proximal and distal regions of the quadriceps muscle group with the cathode being the proximal electrode. Stimuli of 200-μs pulse width and 10-ms inter-stimulus gap were generated by an electrical stimulator (model DS7, Digitimer stimulator, Welwyn, Garden City, UK) modified to deliver a maximum of 1,000 mA output. Electrical stimuli application was displayed online along with the force signal.

Procedures

Maximal stimulation intensity

Maximal stimulation intensity was determined by application of single twitches at rest, with the voltage set at 300 V and the current intensity increasing by 50 mA for each application. Maximal stimulation intensity (hereafter called the maximal intensity) was determined as that beyond which a further increase in current by 50 mA failed to increase the twitch force further.

Percentages of the maximal intensity twitch force

The stimulation intensities required to produce 10 to 100% (in 10% increments) of the force at maximal intensity were determined in a randomized order. Typically, this procedure required application of 2-3 twitches at each percentage of the maximal intensity to identify the appropriate current. Duration of rest between stimuli applications was 2-3 min. These stimulation intensities were then used for the rest of the experiment (hereafter called percentage intensities).

Stimulation during voluntary contractions

Subjects performed an MVC and all subsequent test contractions were performed at 90% of MVC. This contraction level was selected as our laboratory and others have found it to be a near-maximal contraction level that subjects can achieve consistently [Bampouras et al, 2006; Behm et al, 1996; Bülow et al, 1993]. A target line indicating 90% of MVC was displayed on the same screen as the force from which the subjects received visual feedback to help them maintain a steady and consistent force.

The subjects were required to perform 9 trials at 90% of MVC with 3-4 min rest interval. Typically, these trials lasted ~2 s. During each trial, two stimuli (doublet) were applied as soon as a force plateau occurred (determined visually) while a second doublet was applied exactly three seconds later, during complete relaxation (resting doublet). The doublet was selected over a higher number of stimuli based on our previous finding of no differences between a doublet and a quadruplet or an octuplet on the ITT value for the quadriceps muscle (Bampouras et al, 2006). The ITT (eq.1) value for each percentage intensity was calculated.

To assess the level of discomfort associated with a given percentage intensity, an unmarked 10 mm visual analog pain intensity scale (VAS [Collins et al, 1997]), with ‘No pain’ at one end and ‘Worst pain’ at the other end, was used to record the level of discomfort experienced by the subjects after each stimulus intensity. Scores above 5.4 cm indicate severe pain, while scores above 3 cm indicate moderate pain [Collins et al, 1997].

Statistical analysis

Normality of data was examined using the Shapiro-Wilk test and was subsequently confirmed for all variables (90% MVC, activation level, VAS pain scores). A repeated measures analysis of variance was used to ascertain comparability of 90% MVC force across the trials with the different percentage intensities.

Differences between percentage intensities and maximal intensity for activation level and VAS scores were examined using Dunnett's test. This test is more appropriate in situations where several treatments are to be compared against a control or reference treatment only, rather than comparisons between all treatments [Dunnett, 1955]. The smallest percentage intensity for which muscle activation did not differ significantly from that of the maximal intensity was considered to be the minimum intensity able to yield valid results. Significance was set at $p < 0.05$. Values are presented as mean (SD), unless otherwise indicated.

Results

The subjects' MVC force was 748 (130) N. The 90% MVC force was not significantly different ($p = 0.477$) between the trials with the different percentage intensities (Table 1) and demonstrated low variability (coefficient of variation 2.5 (1.2) %). The resting stimulus force at maximal intensity was 302 (62) N (Figure 1).

Table 1

Figure 1

Muscle activation at maximal stimulation intensity was 91.6 (2.5)%. Percentage intensities of 90-50% yielded similar muscle activation values compared to the maximal intensity ($p > 0.05$). However, the percentage intensities of 40-10% produced significantly different muscle activation values ($p < 0.05$) than maximal intensity (Figure 2). Therefore, 50% of maximal intensity was the mean lowest percentage intensity yielding a valid ITT outcome (muscle activation 88.8 (3.9) %).However, visual inspection of individual graphs indicated that in some subjects a valid ITT outcome could be obtained with intensities around 30% of maximal intensity.

Figure 2

Figure 3

VAS indicated that pain at percentage intensities of 90-70% was similar to the pain experienced at maximal intensity. However, pain at 60-10% stimulation intensities was significantly lower ($p < 0.05$). The pain scores were reduced from 6.6 (1.5) cm at maximal intensity to 3.7 (1.5) cm at 60% percentage intensity (Table 1).

Discussion

The aim of the study was to identify the minimum stimulation intensity that will yield valid muscle activation values, similar to those obtained with maximal intensity. We found that stimulation at 50% of maximal intensity is sufficient to obtain a valid ITT outcome. The discomfort experienced by the subjects at this stimulation intensity was also reduced from severe to moderate compared to maximal stimulation.

Many previous authors have used what they term “maximal” stimulation intensities in an attempt to activate the largest portion of muscle possible and avoid erroneous ITT estimates [Behm et al, 2001; de Ruiter et al, 2004; Kent-Braun and Le-Blanc, 1996; Knight and Kamen, 2001; Kooistra et al, 2007; Morse et al, 2008; O’Brien et al, 2008; Reeves et al, 2003]. However, a comparison between percutaneous muscle stimulation, which only activates a proportion of the muscle, and nerve stimulation, which activates all the motor units [Rutherford et al, 1986], showed no differences in the ITT outcome between the two techniques, suggesting that valid results can be achieved as long as the portion of the muscle activated at rest and during contraction remains the same. The findings of the current study support those of Rutherford et al [1986], indicating that reliable ITT results can be obtained even when activating relatively small portions of the quadriceps muscle.

The mechanisms underlying the pattern of the ITT and the results obtained in the present study can be better understood by considering the changes with percentage intensity and the magnitude of the corresponding mean values of the superimposed and resting doublets independently (Figure 1). At lower stimulation intensities (10% and 20% of maximal intensity), a very small proportion of inactive muscle would become activated by the superimposed doublet. Although this stimulation intensity suffices to produce a detectable force increment when the doublet is applied at rest, it is difficult to detect the superimposed doublet since any force increment is small in relation to the oscillation of the voluntary force trace. This results in zero SI/R ratios and a misleading conclusion of complete activation. At 30% and 40% of maximal intensity a larger portion of muscle becomes activated and the magnitude of the superimposed doublet increases rapidly. Following that point the stimulation intensity reaches a level that is sufficiently high to induce both detectable increases in the superimposed stimulus as well as sufficiently stretch the series elastic components at rest, resulting in a constant SI/R ratio and, thus, in valid ITT results.

Maximal stimulation is an imprecise term since it can vary with the type of stimulator, the type, size and position of the electrodes as well as the conductivity of the skin and subcutaneous fat and the size of the muscle. It is therefore more useful to define the minimum requirements for testing activation in terms of the force generated by the electrical stimulation as a percentage of the likely MVC force. In our subjects the mean 90% of MVC was 635 N and reliable estimates of ITT were obtained with a percentage intensity that generated a mean force of 181 N in the resting muscle. Consequently, we recommend that the stimulation intensity should be set to generate at least one third of the estimated MVC.

A concern with electrical stimulation is sometimes the discomfort experienced by subjects [Behm et al, 2001; Chae et al, 1998; Delitto et al, 1992; Han et al, 2006; Miller et al, 2003; Valli et al, 2002]. Two studies have indicated high levels of discomfort in older subjects [Valli et al, 2003] and patients [Chae et al, 1998], subject groups where it is particularly important to assess the ability to activate their muscles [Bampouras et al, 2006; Chae et al, 1998]. Subject discomfort was investigated by Miller et al [2003] by inducing pulse trains of different lengths and durations. Less discomfort was reported with shorter pulse durations without a change in the activation results. Suggestions were made for more research into protocols that can assess muscle activation reliably, with reduced discomfort of the subjects. The present findings suggest that discomfort was significantly reduced at percentage intensities below 60%. The average difference in VAS scores was reduced by 2.9 cm. Previous studies suggested 2 cm as the minimum clinically significant change when using VAS [DeLoach et al, 1998]. Therefore, our results indicate a reduction from severe pain to moderate pain, which is important because it widens the applicability of ITT assessment to subjects who are less tolerant of high intensity stimulation.

Another potential problem with the application of transcutaneous electrical stimulation for assessing activation capacity using the ITT method is co-contraction of: a) nearby agonist muscles due to current spread [Taylor, 2009], b) antagonist muscles due to activation of cutaneous receptors [Belanger and McComas, 1981; Poumarat et al, 1991] and c) antagonist muscles due to discomfort [Paillard et al, 2005]. The latter effect will be less of a problem with submaximal stimulation. Nevertheless, electromyography can be used to detect any artifactual co-contractions from non-studied muscles and make appropriate relevant adjustments (e.g., alter size or position of stimulating electrodes).

In conclusion, this study shows that maximal stimulation is not necessary to obtain a valid ITT outcome. Our results for the knee extensor muscles of healthy young adults show that valid ITT results for contractions at 90% of MVC can be obtained with just 50% of maximal intensity. Practically, a more useful guide is that the force generated by stimulation of the resting muscle should be approximately one third of the anticipated MVC force.

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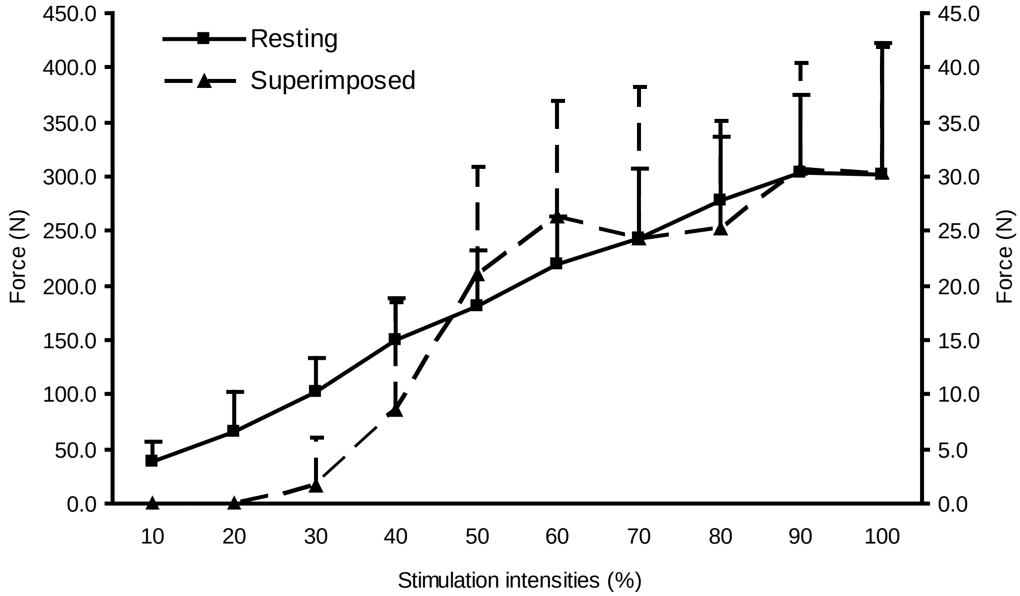
Figure captions

Figure 1. Mean superimposed (left y axis) and resting (right y axis) doublet magnitudes across all percentage intensities. Vertical bars denote SD.

Figure 2. Mean muscle activation values across all percentage intensities. Vertical bars denote SD. * indicates significant difference ($P<0.05$) compared to maximal intensity.

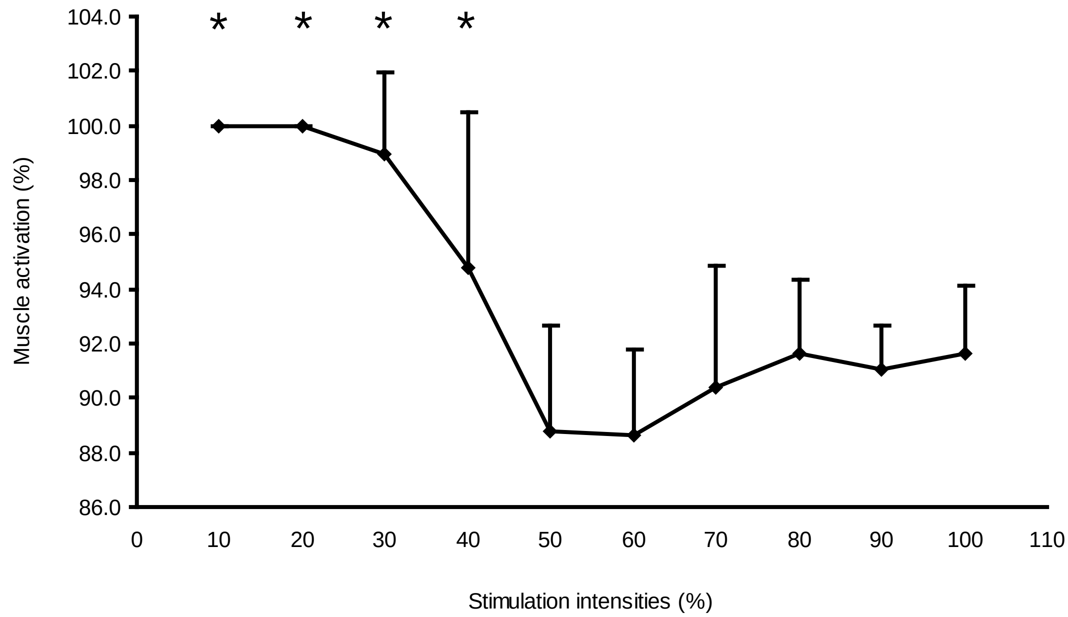
Figure 3. Muscle activation values across all percentage intensities for a single subject, showing a plateau in muscle activation occurring below 30% percentage intensity.

Figure 1.



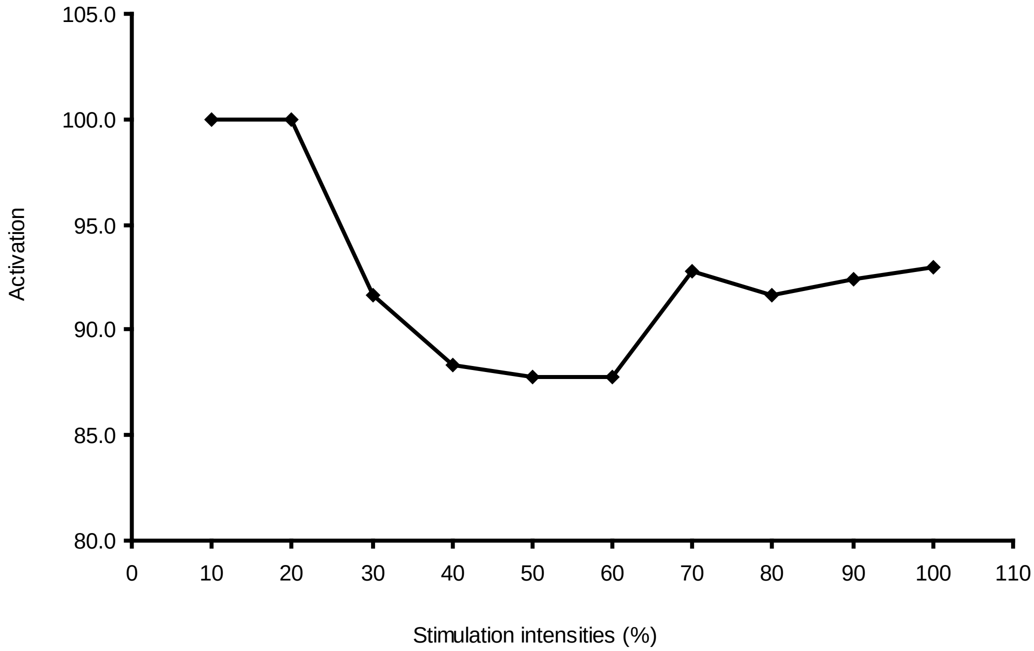
Resting
Superimposed
Force (N)
Force (N)
Stimulation intensities (%)
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
10
20
30
40
50
60
70
80
90
100

Figure 2.



104.0
102.0
100.0
98.0
96.0
94.0
92.0
90.0
88.0
86.0
Muscle activation (%)
* * * *
0 10 20 30 40 50 60 70 80 90 100 110
Stimulation intensities (%)

Figure 3.



105.0
100.0
95.0
90.0
85.0
80.0
Activation
0
10
20
30
40
50
60
70
80
90
100
110
Stimulation intensities (%)

Tables

Table 1. 90% of MVC force values and VAS pain scores for each percentage intensity. Data are presented as mean (SD). * indicates significant difference between a given percentage intensity and the maximal intensity.

	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
90% MVC (N)	639	643	631	631	628	641	626	639	634	636
	(102)*	(110)*	(119)*	(116)*	(114)	(108)	(106)	(108)	(115)	(117)
VAS (cm)	1.5	1.4	1.6	3.0	4.0	3.7	4.4	4.9	6.4	6.6
	(1.9)*	(1.3)*	(1.2)*	(1.7)*	(2.2)*	(1.5)*	(1.7)	(2.3)	(2.5)	(1.5)